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Utilizing Fine Marine Sediment as a Partial Substitute for Sand in Self-Compacting Concrete Specially Designed for Application in Marine Environments

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Abstract: The disposal of marine sediments poses a significant economic and environmental challenge on a global scale. To address this issue and promote resource optimization within a circular-economy paradigm, this research investigates the viability of incorporating untreated fine marine sediments as a partial replacement for sand in self-compacting concrete (SCC) designed especially for application in marine environments (an exposure class of XS2 and a resistance class of C30/37 according to standard NF EN 206). The concretes mis-design incorporating 30% by weight of sediment as a sand substitute was initially designed with the modified Dreux–Gorisse method. The findings indicate that it is feasible to design an SCC suitable for marine environments, incorporating 30% sediment replacement content and without significantly compromising concrete properties, durability, or the estimated lifespan of the formulated concretes. The integration of marine sediment as a sand substitute into the SCC mix design reduces the amount of binder and limestone filler without compromising the paste volume. This results in a significant saving of natural sand resources and a reduction in CO_2 emissions for SCC made with marine sediment.

Keywords: marine sediments; valorization; sand substitution; self-compacting concrete; marine concrete; durability; estimated lifespan; CO_2 emissions

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1. Introduction

After water, sand stands as the second-most exploited and utilized natural resource globally [1]. Its diverse industrial applications include being a crucial raw material in the manufacturing of various commodities such as windows, computers, telephones, road asphalt, and concrete. Among these applications, the construction field, particularly in the context of concrete production, remains the sector with the highest demand for sand [2].

Because of its low cost and its strength and durability, concrete stands as the most extensively employed construction material globally. Besides cement, gravel, and water, the concrete industry utilizes a significant quantity of sand. This sand is incorporated into the concrete mix design to ensure granular continuity between the cement and gravel. It therefore makes a concrete structure [3].

Sand is typically acquired through quarry extraction or dredging from riverbeds. However, in certain regions, the scarcity and escalating costs of river resources are exacerbated by regulatory constraints and/or limited availability. Moreover, the process of crushing rocks to acquire the sandy fraction is challenging and entails substantial energy consumption [4]. However, in specific regions of the Earth, sand is becoming increasingly scarce. In certain instances, the need to transport sand over considerable distances leads to adverse economic and environmental consequences [2]. Consequently, scientific researchers are investigating the possibility of finding an alternative to sand in concrete materials. The alternative materials cited are recycled glass [5], recycled concrete aggregates [6], desert sand [7], marine sediments [8], marble waste [9], coal bottom ash [10], etc. All conducted studies share a common objective of promoting sustainable development by incorporating unconventional materials and recycling industrial waste in concrete production. The utilization of these alternative materials in concrete serves to address the scarcity of natural sand resources and promotes the valorization of waste within a circular economy framework.

Among the various alternatives explored to date, dredged marine sediments have captured researchers' attention over several decades. These sediments result from indispensable dredging operations essential for maintaining port infrastructure. On a global scale, over 100 million tons of sediment are dredged annually. In France, the annual dredging quantity exceeds 30 million tons [11]. The management, disposal, or elimination of these sediments is becoming progressively costlier and subject to stringent regulations, mainly for fine marine sediments.

The predominant valorization method for these sediments in concrete materials involves a calcination process between 750 °C and 850 °C. This process is designed to improve the physicochemical characteristics and stimulate the pozzolanic properties of dredged marine sediments. The calcinated sediments are then used as supplementary cementitious materials (as a substitute for cement) in concrete mix design [12–15]. For example, Safhi et al. found that the replacement of cement by 10% (by weight) of calcinated marine sediment (dredged from Dunkirk Harbour) in SCC does not impact the hardened and microstructural properties of the concrete samples [16]. Amar et al. demonstrated that replacing 10% of Portland cement with calcinated marine sediment (dredged from Dunkirk Harbour) does not affect the durability of the examined specimens (mortar) [17].

Despite the extensive research on utilizing treated marine sediment as a supplementary cementitious material, the economic and the environmental (CO_2 impact) costs associated with this valorization method remain particularly high. This is primarily attributable to the energy-intensive calcination process at 750 °C, which diminishes the overall environmental and economic benefits. Furthermore, the applicability of these laboratory-based approaches to real-world situations is not necessarily straightforward due to the substantial volumes of marine sediment involved and the lack of industrial facilities close to dredging sites. This increases the costs and the CO_2 emissions of transporting fine sediments from the dredged location to the industrial treatment site.

However, considering the drawbacks associated with the calcination process and the scarcity of sand, numerous studies have been published on the utilization of dredged marine sediment as sand substitute in concrete materials. Elmoueden et al. investigated the impact of partially substituting sand with dredged marine sediments at levels of 15%, 30%, and 50% in the fabrication of foamed concretes. Their results indicated that the substitution of sand resulted in an increase in both the compressive strength and density of the concrete specimens [18]. Moradi and Shahnoori found that replacing sand with dredged marine sediment at levels below 25% led to an enhancement in compressive strength, coupled with a reduction in permeability and water absorption of the investigated samples. Conversely, a decrease in the mechanical strength of the concrete specimens was observed when the percentage of dredged marine sediment exceeded 35% [8]. Ben Allal et al. noted a 30% decrease in the mechanical strength of mortar specimens when 20% of sand was substituted by raw marine sediment [19]. Nevertheless, as shown above the incorporation of dredged marine sediment in concrete mix design as partial substitution of sand has shown mixed results. Therefore, the valorization of dredged marine sediment through sand substitution in concrete materials requires further investigation and research. According to Kazi Aoual-Benslafa et al., for the proper incorporation of dredged marine sediment as sand replacement in concrete production, it is imperative for it to undergo appropriate treatment [20]. This is because of the existence of salts, along with organic and inorganic pollutants found in sediments [20,21]. Scientific evidence has substantiated that the presence of salts and pollutants can impact the characteristics and properties, such as cement hydration reactions and structural strength development, of concrete manufactured with dredged marine sediments, [22]. However, in a prior investigation, Hayek et al. demonstrated that incorporating up to 30% of untreated marine sediment in concrete material does not significantly impact the potential durability and estimated lifespan of the concrete specimens. Achieving successful integration of this incorporation requires an initial optimization of the concrete mix design [23].

Then, to the best of our knowledge, research on the incorporation of marine raw sediments without any treatment or granular separation into the sandy component of SCC remains infrequent. Ouédraogo et al. utilized granular separation at 125 µm before integrating untreated marine sediments as a substitute for sand in SCC. They found that the percentage of particles less than 125 µm affect the stability of SCC [24]. In the study of Rozas et al., a decontamination step was used prior to the integration of sediments as sand or as filler substitute in SCC mix design. The authors found that the fluidity and the cohesivity of SCC were affected by the use of treated marine sediments [25].

Hence, considering the environmental and economic advantages of utilizing untreated marine sediments in concrete [26], further research is needed to confirm the feasibility of using these sediments directly as a replacement for sand in SCC. It is essential to evaluate how this incorporation affects both the fresh and hardened properties of SCC to enable its industrial utilization in the precast concrete market.

2. Research Objectives

The objective of this present research is to demonstrate the viability of substituting natural sand with untreated fine marine sediments (from Port-Camargue, with a particle size of approximately 100 to 150 microns) in the fabrication of self-compacting concrete suitable for the submerged marine environment (i.e., exposure class XS2 and resistance class C30/37). Incorporating fine marine sediment into the mix design of SCC facilitates the industrial valorization of dredged sediments within the precast concrete market. Then, the ultimate objective is to propose an economically and environmentally sustainable industrial solution within a circular economy framework, addressing the utilization of fine sediments in the sandy component of concrete materials.

3. Materials and Methods

3.1. Dredged Marine Sediments

The fine dredged marine sediments used in this research were sourced from Port-Camargue, located in Grau du Roi, France. Figure 1 shows the geographic coordinates of the dredging operation sites. Sediments obtained from all dredging sites were combined, and the anticipated sediment fraction was isolated based on particle weight through hydrocyclone separation, followed by dewatering using geotextile tubes. Subsequently, the samples collected from the geotextile tubes were hermetically sealed in plastic bags and stocked in the laboratory at 20 °C until use. It is noteworthy that this sediment exhibited no contamination by polycyclic aromatic hydrocarbons, heavy metals, or polychlorinated biphenyls [23].

The chemical and the physical properties of these dredged marine sediments are outlined in Table 1 (refer to [23] for additional details). Prior to incorporation into the concrete material, the sediments underwent a 48 h air-drying process at room temperature, resulting in a reduction in their water content to around 10%.

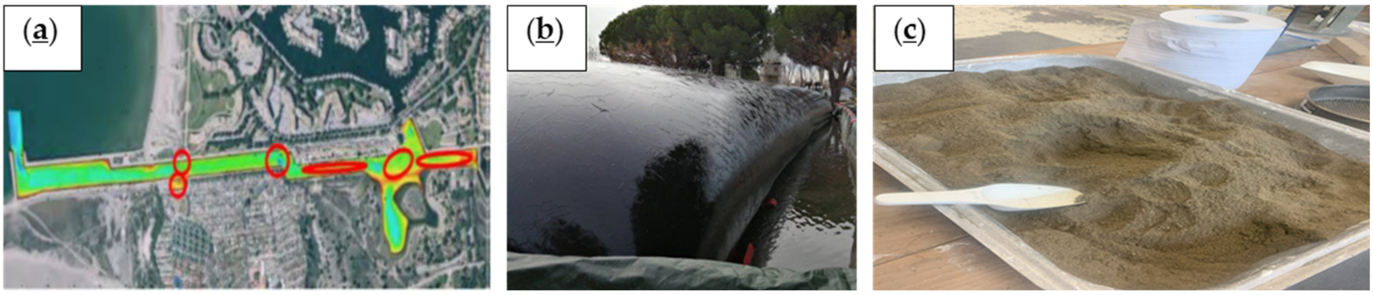

Figure 1. Site location of the dredging operation conducted in Chenal Sud (**a**), bleeding of fine marine sediments in geotextile tubes (**b**), Port-Camargue, France. Sediments were ready to use in the laboratory (**c**).

Table 1. Physio-chemical properties of the marine sediments used in this study.

Water Content	17.7 ± 5.6%
Average diameter	117.5 µm ± 25 µm
Median diameter	94.4 µm ± 27 µm
Density	2.66 ± 0.01 g/cm^3
Specific surface area	3.13 ± 0.82 m^2/g
pH	8.67 ± 0.13
Clay content	0.81 ± 0.25%
Chloride content	0.67 ± 0.15%
Total organic carbon	2.69 ± 0.26%
Morphology	Angular shape
Major mineral elements	Calcite ($CaCO_3$), Quartz (SiO_2) and Anhydrite ($CaSO_4$)
Major chemical composition	SiO_2 (52.84%), Al_2O_3 (9.56%), Fe_2O_3 (3.15%), CaO (13.25%), K_2O (3.30%), Na_2O (1.48%), MgO (1.40%)

3.2. Concrete Specimens Mix Designs

The SCC samples investigated in this research were prepared with a blended cement (composed of 70% Portland cement 52.5 N and 30% Ground Granulated Blast-furnace Slag), a water-to-cement ratio of 0.5, sand (0/4, Languedoc Roussillon Matériaux, LRM), gravel (natural silica-limestone 6.3/14, LRM), a limestone filler and a superplasticizer (SP) with high water-reducing properties (Table 2).

Table 2. Mix designs (Kg/m^3) of concrete samples investigated in this research.

	Reference (0%)	**Sediment (30%)**
Gravel 6.3/14	730	888 (+21%)
Sand	888	595 (−33%)
Marine sediment	0	250
CEM1 52.5	260	245 (−5%)
GGBS, Ecocem@	111	105 (−5%)
Limestone filler	110	50 (−45%)
Effective water	180	170 (−5.5%)
w/b ratio	0.5	0.5
Mixing water	200	211
Superplasticizer (%)	0.2	1
Paste volume (L)	356	357

The Dreux–Gorisse [27] was employed to establish the optimized mix design of the concrete samples with the targeted medium mechanical strength of 38 MPa at 28 days

(C30/37, marine concrete XS2). According to this method, the mix design of the SCC made with 30% of marine sediment was different from that of the reference concrete. For example, the quantity of gravel was 21% grater in the case of SCC made with marine sediment.

The concrete produced was assessed for its workability, water porosity (water penetration under pressure), water absorption, and compressive strength.

For the concrete incorporating dredged marine sediment, the sediment with water content of 10% was used as a partial substitute of sand at a rate of 30% (*w*/*w*). Then, the amount of added limestone filler and blended cement was modified to achieve an equivalent paste volume to that of the reference (357 L/m^3). The amount of superplasticizer was modified to achieve a minimum of 600 mm in the slump-flow test.

The SCC samples preparation involves the following steps (Figure 2): the solid components (i.e., gravel, sand, binder, limestone filler and sediments) were initially introduced and mixed for 60 s. Subsequently, water was added gradually. After 90 s, the superplasticizer was introduced, and the components were mixed for an additional 90 s.

Figure 2. Self-compacting concrete preparation process.

Following the mixing process, cylindrical specimens were cast using cylindrical cardboard molds (diameter of 110 mm, height of 220 mm), covered with a plastic lid. After the curing step of 24 h, the concrete specimens were demolded and submerged in water at 20 °C.

In Table 2, the quantities of materials utilized in the concrete containing 30% marine sediment were compared to those of the reference concrete (0%). While this basic comparison provides a quick analysis of the situation, it may not accurately assess the impact of incorporating fine marine sediment into concrete on CO_2 emissions. Further investigation into this matter is required through life-cycle assessment and life-cycle cost assessment [26].

3.3. Test of the Fresh SCC

The analysis of the SCC properties in the fresh-state was limited to the tests recommended by AFGC [28], which included sieve stability and slump-flow tests conducted after 0 and 30 min of the mixing process. The sieve stability (Figure 3) (NF EN 12350-11) [29] and slump flow (Figure 4) (NF EN 12350-8) [30] tests were performed on three different SCC obtained with an individual mixing process.

Figure 3. SCC under sieve analysis test.

Figure 4. SCC under slump-flow test.

The sieve stability test is designed to assess the risk of static segregation and investigate bleeding in SCC. After mixing, SCC was poured onto a 5 mm sieve from a height of 50 cm. After 15 min, the mass percentage of bleeding that has passed through the sieve was measured and compared to the mass of the initial sample.

The slump flow test is designed to assess the workability of SCC. After mixing, the SCC was added to Abram's cone. Then, the diameter of the resulting spread disc was measured. The targeted slump flow was 650 $\pm$ 50 mm which gives an SCC. Then, the impact of marine sediment on the workability of SCC was assessed based on the quantity of SP added to attain the desired slump flow.

3.4. Test of the Hardened SCC

Table 3 provides a summary of the experimental tests employed, along with the size and quantity of specimens investigated in this study.

Table 3. The size and the number of tested samples in each experimental test performed in this study.

Experimental Test	Concrete Specimens: Reference (0%) and Sediment (30%)		
	Sample Size (Diameter, High)	**Curing Period (Days)**	**Number of Tested Samples**
Sieve stability	Fresh state		3
Slump-flow test	Fresh state		3
Compressive strength	110 mm, 220 mm	1, 14, 28, or 90	3/period
Water absorption and	110 mm, 50 mm	28	3
water porosity	110 mm, 50 mm	28	3
Gas permeability	118 mm, 50 mm	90	3

3.4.1. Compressive Strength

Compressive strength experiments (MPa) were conducted in accordance with the NF EN 12390-3 standards [31]. Three specimens of reference SCC and SCC made with 30% of marine sediment were tested at 1, 14, 28, and 90 days using a compression testing machine (3R, Montauban, France) (Figure 5).

Figure 5. SCC at 28 days under Compressive strength test.

3.4.2. Water Absorption and Water Porosity

Tests of water absorption (Water Absorption by Immersion, WAI) and water porosity were performed in triplicate after 28 days of curing. Three samples (i.e., diameter of 110 mm and high of 50 mm) of SCC specimens were kept in water for 48 h at atmospheric pressure for water absorption and under saturation pressure for water porosity. An oven-drying process at 105 °C was used. Then, the dry mass of the samples was measured.

3.4.3. Gas Permeability

Gas permeability tests were performed at 90 days using CEMBUREAU permeameter (Figure 6) according to standard XP P18-463 [32]. To achieve accurate intrinsic permeability measurements, the CEMBUREAU test includes fifteen measurements of apparent permeability on three different samples (i.e., diameter of 118 mm and height of 50 mm).

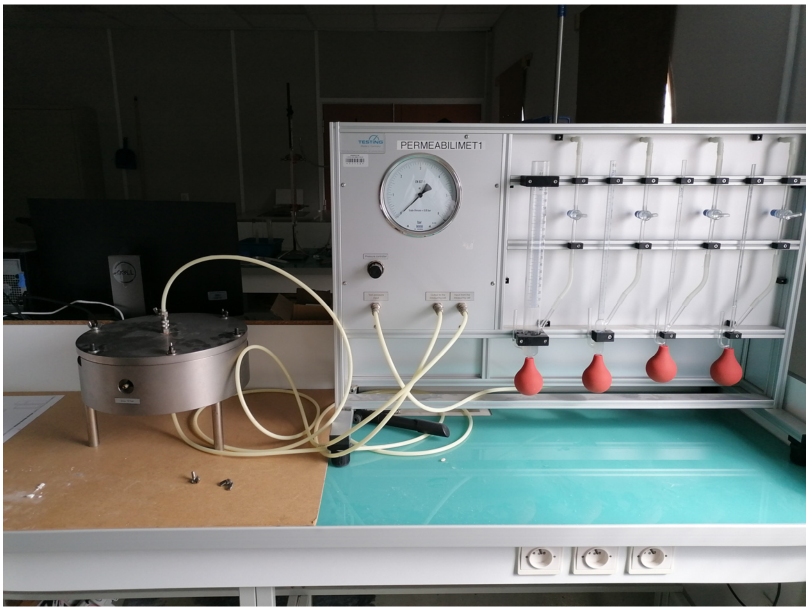

Figure 6. CEMBUREAU permeameter device.

3.4.4. Statistical Analysis

To evaluate the impact of marine sediment on SCC properties, a statistical analysis was performed using one-way ANOVA tests conducted through GraphPad Prism 5 (GraphPad Software, San Diego, CA, USA).

4. Results and Discussion

4.1. Influence of Marine Sediment on the Fresh State of SCC

Table 4 shows the influence of marine sediment on the fresh state of SCC 0 and 30 min after the mixing process. Incorporating marine sediment into the concrete mix design necessitates an augmentation in the amount of SP required to attain the targeted flow in the slump test. The amount of added SP increased from 0.2% to 1% (% by binder weight) when 30% of marine sediment was used in substitution of sand. These findings align with the research conducted by Hayek et al., where it was reported that the amount of superplasticizer required to achieve the desired slump increases with increased substitution of sand by marine sediment [23]. Moreover, these findings align with the research conducted by Limeira et al., wherein it was also noted that additional SP content is necessary to attain the targeted slump when sand is substituted by marine sediment [33].

Table 4. Effect of marine sediment on the fresh state of SCC.

	Reference (0%)	**Sediment (30%)**
Superplasticizer	0.2%	1%
Flow spread (0 min)	72.5 ± 0.71 cm	64.5 ± 0.71
Flow spread (30 min)	61.5 ± 0.71 cm	62.5 ± 0.71
T_{50} (0 min)	1.18 s	2.38 s
T_{50} (30 min)	4.18 s	3.01 s
Sieve stability	4.9%	7.3%

Table 4 shows that the incorporation of marine sediment in the concrete mix design does not affect the flow spread of SCC and the time required to reach a diameter of 50 cm (T_{50}) even 0 and 30 min after the mixing process. The flow spreads were 61.5 and 62.5 cm, respectively, after 30 min of the mixing process for the reference SCC and 30% sediment SCC. Subsequently, the initial decrease in workability induced by the incorporation of marine sediment can be restored by adding SP. This finding is very important, especially in the case of SCC, where workability is a crucial property denoting the SCC's capacity for reshaping, movement, and consolidation [34].

In the case of the sieve-stability test, Table 4 shows that both the reference SCC and the 30% sediment SCC exhibit a segregation rate below 15%. This suggests that the incorporation of marine sediment does not affect the stability of SCC in its fresh state.

Hence, in this research, the partial replacement of sand by marine sediment in the mix design of SCC only impacts the quantity of superplasticizer added to achieve the desired workability. This increase will not affect the economic and environmental advantages of SCC made with marine sediment; in a previous study published in 2022, Soleimani et al. showed that exceeding a 1.5% consumption of SP to alleviate the side effects of sediment on the workability of concrete can mitigate the economic cost and the environmental benefits of substituting sand by marine sediment [26]. Furthermore, this study revealed that integrating marine sediment as a sand substitute into the SCC mix design reduces the amount of binder and filler without compromising the paste volume (Table 2). The amount of binder and filler used in the SCC mix design decreased by 10% and 45%, respectively when marine sediment was used. This results in a reduction in the CO_2 emissions of SCC made with marine sediment [35]. Given that CO_2 emission per kilogram of cement production falls within the range of 0.5 to 0.9, a reduction of 15 kg (10%) of cement in the SCC made with marine sediment would result in a decrease of at least 7.5 kg of CO_2 emissions per ton of this concrete [36]. In addition, the use of marine sediment as substitute of sand in the concrete fabrication allows a significant saving of natural sand resources which are becoming scarce in certain regions of the Earth.

4.2. Effect of Marine Sediment on the Hardened State of SCC

Figure 7 shows the effect of marine sediment on the hardened state of SCC specimens. The results indicate that the incorporation of 30% of marine sediment as a sand substitute in the SCC mix design significantly affects the mechanical resistance of concrete specimens. The decrease in compressive strength was 25, 20, 10, and 9% at 1, 7, 28, and 90 days. These results align with the research conducted by Moradi and Shahnoori, where the compressive strength of concrete specimens was negatively impacted when the marine sediment content exceeded 15% [8]. According to Bedaa et al., the decrease in the mechanical strength of concrete made with marine sediment as partial substitute of sand can be attributed to the fine particles of sediments which affect the properties of cement paste, as well as the chemical composition of marine sediment (i.e., salt content) [35]. However, concrete specimens made with 30% of marine sediment achieve the targeted mechanical strength of 38 MPa at 28 days. Therefore, 30% of marine sediment can be used as a substitute for sand in marine-grade (XS2) SCC.

In the marine environment, the water porosity, water absorption, and gas permeability of concrete significantly impact the primary durability issues in seawater (i.e., external aggression and chloride penetration) as well as the overall service life of the concrete material [23,37–39]. In the case of SCC in marine environment, a robust correlation between the chloride diffusion and porosity, and gas permeability and porosity was reported. A low gas permeability and a low passing charge were found to be associated with low water porosity [40]. In this study, the incorporation of marine sediment at a percentage of 30% as sand-replacement does not significantly affect the water porosity, the water absorption and the gas permeability of concrete specimens. The water porosity was 11.9 and 12.2% in the case of reference concrete and concrete made with 30% sediment, respectively (Figure 7). The water absorption increases from 4.6 to 4.9% when 30% of sand were substituted by marine sediment. The gas permeability was 141.8 and 180.9 in the case of SCC made with 0 and 30% of marine sediment, respectively. According to the values obtained with the four durability indicators measured in this study, namely, compressive strength, water porosity, water absorption, and gas permeability, the SCC made with 30% of fine marine sediment has the same durability (medium) and the same lifetime (50–100 years) of SCC made with natural crushed sand [23,41].

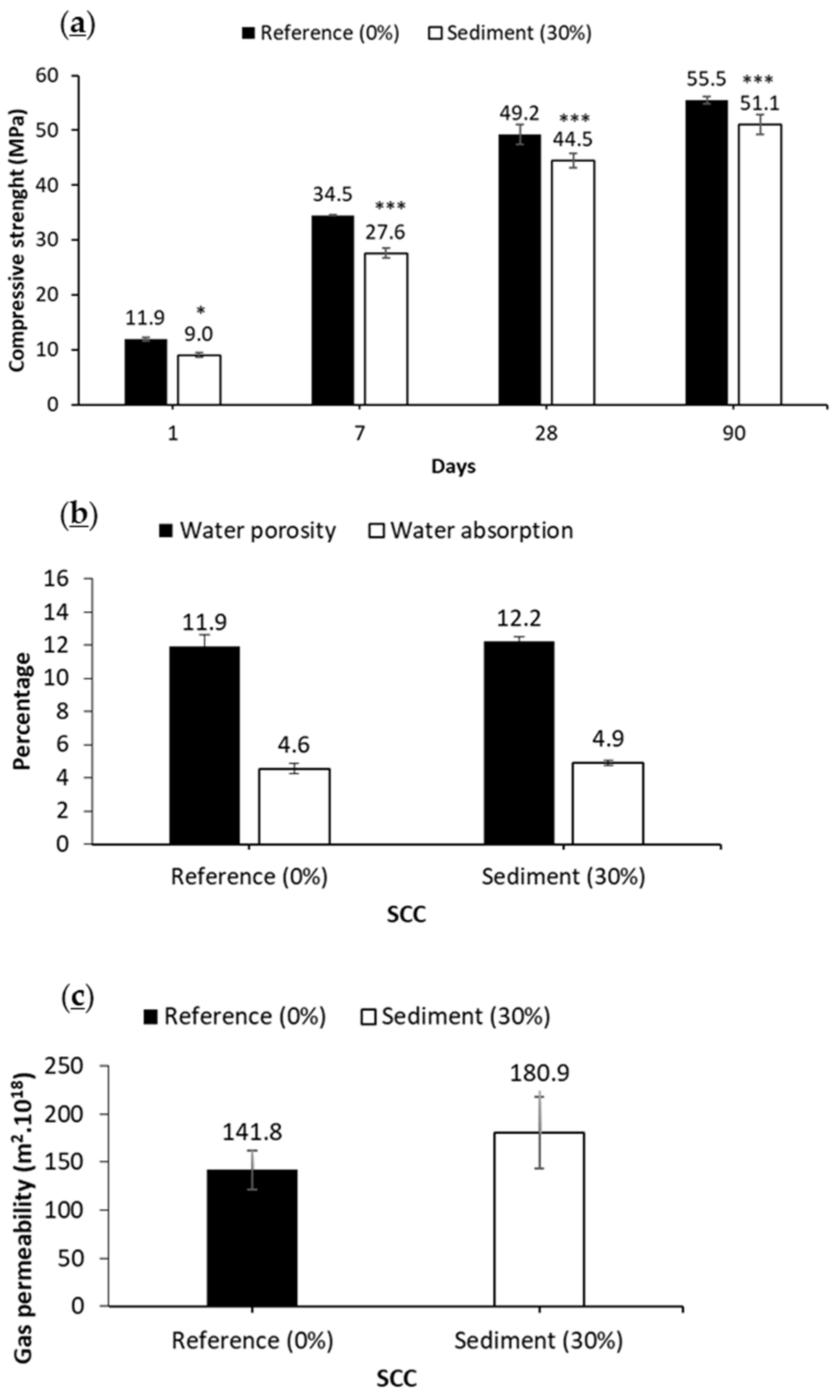

Figure 7. Effect of marine sediment on the compressive strength (**a**), water porosity (**b**), water absorption (**b**), and gas permeability (**c**) of the SCC specimens. All experiments were conducted in triplicate, and the error bars represent the standard deviation of the measured values. Experiments marked with asterisks exhibited significant differences from the reference (Bonferroni; *: $p < 0.05$, ***: $p < 0.001$).

Therefore, based on the results obtained in the hardened state, it is feasible to design XS2 SCC C30/37 (marine-grade concrete) with a substitution of 30% of sand by marine sediment (which has the same physio-chemical properties as the sediment presented in this study) without causing a significant impact on the potential durability and estimated lifetime of the concrete material. This result agrees with the results obtained in a previous study which showed that 30% of fine marine sediment can be used to design a marine conventional concrete with 30% of fine marine sediment [23]. Indeed, self-compacting concrete (SCC) offers numerous advantages in both production and placement when compared to conventional concrete. These include the elimination of the need for external or internal vibration for compaction, improved flowability, workability, and pumpability, and an enhanced bonding with densely packed reinforcement. However, industries commonly utilize self-compacting concrete for precast concrete applications. Therefore, incorporating fine marine sediment into the mix design of SCC facilitates the industrial valorization of dredged sediments within the precast concrete market.

5. Conclusions

Given the substantial annual volume of dredged marine sediments and the continually growing need for construction materials, the investigation of a novel category of material utilizing dredged sediments is a global opportunity with economic and environmental implications. This study investigates the impact of untreated marine sediments, used as a substitute for sand, on the workability, compressive strength, water porosity, water absorption, and gas permeability of self-compacting concrete specimens. The following conclusions can be drawn from the outcomes of this experimental investigation:

- The incorporation of marine sediment as a sand substitute in the mix design of SCC only impact the amount of superplasticizer required to achieve the targeted workability in the fresh state.
- The integration of marine sediment as sand substitute into the SCC mix design reduces the amount of binder (reduction of 10%) and limestone filler (reduction of 45%) without compromising the paste volume. This results in a reduction in CO_2 emissions for SCC made with marine sediment.
- A marine-grade self-compacting concrete (XS2 SCC C30/37) can be designed with a substitution of 30% of sand by marine sediment without significantly affecting the potential durability and estimated lifetime of the concrete material. This leads to a significant saving of natural sand resources, which are becoming scarce in certain regions of the earth.

This paper presents part of the results of the ECODREGE MED II project. According to the results obtained, the following aspects could be investigated:

- Assessing the economic and environmental impact of the SCC incorporating marine sediments through life-cycle assessment and life-cycle cost-assessment.
- Examining the impact of substituting 30% of sand with marine sediment on the durability parameters of SCC as chloride diffusion.
- Piloting the construction of a marine concrete structure by partially substituting sand with dredged marine sediments, in collaboration with the concrete industry. Given that the amount of SP used in concrete made with fine sediment remains reasonable (1%), the optimized mix design presented in this study has been approved by a precast concrete producer.
- Examining the impact of adding fine marine sediment to SCC on the rheological behavior and the microstructure of concrete.

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References

1. Henry Sonna, O.; Evelyn, U.; Joseph Edewor, A.; Francis Chuks, A. Sand Mining: Economic Gains, Environmental Ethics, and Policy Implications. *Afr. J. Econ. Sustain. Dev.* **2022**, *5*, 119–138. [CrossRef]
2. Peduzzi, P. Sand, Rarer than One Thinks: UNEP Global Environmental Alert Service (GEAS)—March 2014. Available online: https://wedocs.unep.org/handle/20.500.11822/8665 (accessed on 6 July 2022).
3. Zeghichi, L.; Benghazi, Z.; Baali, L. The Effect of the Kind of Sands and Additions on the Mechanical Behaviour of S.C.C. *Phys. Procedia* **2014**, *55*, 485–492. [CrossRef]
4. Kaufmann, J. Evaluation of the Combination of Desert Sand and Calcium Sulfoaluminate Cement for the Production of Concrete. *Constr. Build. Mater.* **2020**, *243*, 118281. [CrossRef]
5. Mardani-Aghabaglou, A.; Tuyan, M.; Ramyar, K. Mechanical and Durability Performance of Concrete Incorporating Fine Recycled Concrete and Glass Aggregates. *Mater. Struct. Mater. Constr.* **2015**, *48*, 2629–2640. [CrossRef]
6. Khatib, J.M. Properties of Concrete Incorporating Fine Recycled Aggregate. *Cem. Concr. Res.* **2005**, *35*, 763–769. [CrossRef]
7. Al-Harthy, A.S.; Halim, M.A.; Taha, R.; Al-Jabri, K.S. The Properties of Concrete Made with Fine Dune Sand. *Constr. Build. Mater.* **2007**, *21*, 1803–1808. [CrossRef]
8. Moradi, S.; Shahnoori, S. Eco-Friendly Mix for Roller-Compacted Concrete: Effects of Persian-Gulf-Dredged Marine Sand on Durability and Resistance Parameters of Concrete. *Constr. Build. Mater.* **2021**, *281*, 122555. [CrossRef]
9. Benhalilou, M.I.; Belachia, M.; Houari, H.; Abdelouahed, A. The Study of the Characteristics of Sand Concrete Based on Marble Waste Sand. *Civ. Environ. Eng. Rep.* **2020**, *30*, 130–144. [CrossRef]
10. Pushkar, S. Life-Cycle Assessment of the Substitution of Sand with Coal Bottom Ash in Concrete: Two Concrete Design Methods. *Appl. Sci.* **2019**, *9*, 3620. [CrossRef]
11. Agostini, F.; Skoczylas, F.; Lafhaj, Z. About a Possible Valorisation in Cementitious Materials of Polluted Sediments after Treatment. *Cem. Concr. Compos.* **2007**, *29*, 270–278. [CrossRef]
12. Dang, T.A.; Kamali-Bernard, S.; Prince, W.A. Design of New Blended Cement Based on Marine Dredged Sediment. *Constr. Build. Mater.* **2013**, *41*, 602–611. [CrossRef]
13. Ez-zaki, H.; Diouri, A. Microstructural and Physicomechanical Properties of Mortars-Based Dredged Sediment. *Asian J. Civ. Eng.* **2018**, *20*, 9–19. [CrossRef]
14. Hadj Sadok, R.; Belas, N.; Tahlaiti, M.; Mazouzi, R. Reusing Calcined Sediments from Chorfa II Dam as Partial Replacement of Cement for Sustainable Mortar Production. *J. Build. Eng.* **2021**, *40*, 102273. [CrossRef]
15. Van Bunderen, C.; Snellings, R.; Vandewalle, L.; Cizer, Ö. Early-Age Hydration and Autogenous Deformation of Cement Paste Containing Flash Calcined Dredging Sediments. *Constr. Build. Mater.* **2019**, *200*, 104–115. [CrossRef]
16. Safhi, A.e.M.; Rivard, P.; Yahia, A.; Henri Khayat, K.; Abriak, N.E. Durability and Transport Properties of SCC Incorporating Dredged Sediments. *Constr. Build. Mater.* **2021**, *288*, 123116. [CrossRef]
17. Amar, M.; Benzerzour, M.; Safhi, A.e.M.; Abriak, N.E. Durability of a Cementitious Matrix Based on Treated Sediments. *Case Stud. Constr. Mater.* **2018**, *8*, 258–276. [CrossRef]
18. Elmoueden, H.; Amar, M.; Zambon, A.; Benzerzour, M.; Abriak, N.-E. The Use of Dredged Marine Sediment in the Formulation of Air–Foam Concrete. *Waste Biomass Valorization* **2022**, *13*, 2591–2607. [CrossRef]
19. Ben Allal, L.; Ammarri, M.; Frar, I.; Azmani, A.; Belmokhtar, N.E. Caractérisation et Valorisation Des Sédiments de Dragage Des Ports de Tanger et Larache (Maroc). *Rev. Paralia* **2011**, *4*, 5.1–5.13. [CrossRef]
20. Kazi Aoual-Benslafa, F.; Kerdal, D.; Mekerta, B.; Semcha, A. The Use of Dredged Sediments as Sand in the Mortars for Tunnel Lining and for Environmental Protection. *Arab. J. Sci. Eng.* **2014**, *39*, 2483–2493. [CrossRef]
21. Wang, Q.; Li, J.S.; Xue, Q.; Poon, C.S. Immobilization and Recycling of Contaminated Marine Sediments in Cement-Based Materials Incorporating Iron-Biochar Composites. *J. Hazard. Mater.* **2022**, *435*, 128971. [CrossRef] [PubMed]
22. Amar, M.; Benzerzour, M.; Kleib, J.; Abriak, N.E. From Dredged Sediment to Supplementary Cementitious Material: Characterization, Treatment, and Reuse. *Int. J. Sediment Res.* **2021**, *36*, 92–109. [CrossRef]
23. Hayek, M.; Soleimani, T.; Salgues, M.; Souche, J.-C.; Garcia-Diaz, E. Valorization of Uncontaminated Dredged Marine Sediment through Sand Substitution in Marine Grade Concrete. *Eur. J. Environ. Civ. Eng.* **2023**, *27*, 4008–4025. [CrossRef]
24. Ouédraogo, N.P.; Becquart, F.; Benzerzour, M.; Abriak, N.E. Influence of Fine Sediments on Rheology Properties of Self-Compacting Concretes. *Powder Technol.* **2021**, *392*, 544–557. [CrossRef]

25. Rozas, F.; Castillo, A.; Martínez, I.; Castellote, M. Guidelines for Assessing the Valorization of a Waste into Cementitious Material: Dredged Sediment for Production of Self Compacting Concrete. *Mater. Constr.* **2015**, *65*, e057. [CrossRef]
26. Soleimani, T.; Hayek, M.; Junqua, G.; Salgues, M.; Souche, J.-C. Environmental, Economic and Experimental Assessment of the Valorization of Dredged Sediment through Sand Substitution in Concrete. *Sci. Total Environ.* **2023**, *858*, 159980. [CrossRef] [PubMed]
27. Hamza, C.; Bouchra, S.; Mostapha, B.; Mohamed, B. Formulation of Ordinary Concrete Using the Dreux-Gorisse Method. *Procedia Struct. Integr.* **2020**, *28*, 430–439. [CrossRef]
28. AFGC. *Recommandations Pour l'emploi Des Bétons Auto-Plaçants*; AFGC: Griffith, Australia, 2008.
29. *EN 12350-11*; Testing Fresh Concrete—Part 11: Self-Compacting Concrete—Sieve Segregation Test. iTeh Standards: Newark, DE, USA, 2010.
30. *EN 12350-8*; Testing Fresh Concrete—Part 8: Self-Compacting Concrete—Slump-Flow Test. iTeh Standards: Newark, DE, USA, 2019.
31. *EN 12390-3*; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. iTeh Standards: Newark, DE, USA, 2002.
32. *XP P18-463*; Concrete—Testing Gas Permeability on Hardened Concrete. Association Francaise de Normalisation: Paris, France, 2013.
33. Limeira, J.; Agullo, L.; Etxeberria, M. Dredged Marine Sand in Concrete: An Experimental Section of a Harbor Pavement. *Constr. Build. Mater.* **2010**, *24*, 863–870. [CrossRef]
34. Seif, E.S.S.A. Assessing the Engineering Properties of Concrete Made with Fine Dune Sands: An Experimental Study. *Arab. J. Geosci.* **2013**, *6*, 857–863. [CrossRef]
35. Beddaa, H.; Ben Fraj, A.; Lavergne, F.; Torrenti, J.M. Reuse of Untreated Fine Sediments as Filler: Is It More Beneficial than Incorporating Them as Sand? *Buildings* **2022**, *12*, 211. [CrossRef]
36. Fayomi, G.U.; Mini, S.E.; Fayomi, O.S.I.; Ayoola, A.A. Perspectives on Environmental CO2 Emission and Energy Factor in Cement Industry. *IOP Conf. Ser. Earth Envion. Sci.* **2019**, *331*, 012035. [CrossRef]
37. Diamond, S. Aspects of Concrete Porosity Revisited. *Cem. Concr. Res.* **1999**, *29*, 1181–1188. [CrossRef]
38. Kumar, R.; Bhattacharjee, B. Porosity, Pore Size Distribution and in Situ Strength of Concrete. *Cem. Concr. Res.* **2003**, *33*, 155–164. [CrossRef]
39. Touil, B.; Ghomari, F.; Khelidj, A.; Bonnet, S.; Amiri, O. Durability Assessment of the Oldest Concrete Structure in the Mediterranean Coastline: The Ghazaouet Harbour. *Mar. Struct.* **2022**, *81*, 103121. [CrossRef]
40. Laidani, Z.E.A.; Benabed, B.; Abousnina, R.; Gueddouda, M.K.; Kadri, E.H. Experimental Investigation on Effects of Calcined Bentonite on Fresh, Strength and Durability Properties of Sustainable Self-Compacting Concrete. *Constr. Build. Mater.* **2020**, *230*, 117062. [CrossRef]
41. AFGC. *Maîtrise de La Durabilité Vis-à-Vis de La Corrosion Des Armatures et de l'alcali-Réaction—Etat de l'art et Guide Pour La Mise En Œuvre d'une Approche Performantielle et Prédictive Sur La Base d'indicateurs de Durabilité*; AFGC: Griffith, Australia, 2004.